The Thesis Committee for Janna Hayes LaRocco
Certifies that this is the approved version of the following thesis:

Thermal Imaging of a Selective Laser Sintering Part Bed Surface

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor:

David Bourell

Joseph Beaman

Thermal Imaging of a Selective Laser Sintering Part Bed Surface

by

Janna Hayes LaRocco, B.S.

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

December 2010

Abstract

Thermal Imaging of a Selective Laser Sintering Part Bed Surface

Janna Hayes LaRocco, MSE

The University of Texas at Austin, 2010

Supervisor: David Bourell

In an effort to gain a more comprehensive and complete understanding of the thermal behaviors occurring during the selective laser sintering process, external temperature measurements were taken during the build process. To accomplish this, an infrared camera was aimed directly through a viewport on the front of the sinterstation. The temperature was monitored during the heating process which showed slightly non-uniform heating of the part bed surface. Temperatures were also recorded while the laser was sintering each layer and the subsequent cooling of the entire machine following the build. By directly capturing infrared images of the part bed's surface, it is clearer how the temperature gradients behave and the impact such variables have on part build efficiency.

Table of Contents

List of Figures

Chapter 1: Basic Concepts and Previous Work

Selective laser sintering (SLS) is a form of additive manufacturing that utilizes a high-powered laser to melt particles. After a three-dimensional part is modeled using computer-aided design (CAD) software, the file is uploaded to a sinterstation (Figure 1). Once the file has been uploaded and the build begins, a thin layer of powder is deposited across a part bed build chamber. The laser sinters the powder particles to form a single layer of the part. After the layer has cooled, the part bed chamber drops to a specified depth. Another layer of powder is spread evenly across the previously sintered layer, and the process is repeated continuously until the desired part has been formed.

Figure 1: Front view of *Sinterstation 2500* [1]

SLS has several advantages over other forms of rapid prototyping. Because the process is based on a CAD model, the sinterstation is able to manufacture completely customizable parts with complex geometries. Also, SLS does not need any customized tooling to create parts, so individual prototypes can be created one at a time. An added advantage to SLS is its ability to build parts without any use of external supports. A sinterstation does not need external supports because of the successive building of layers on top of each other within a powder-filled chamber. The previously sintered layers and surrounding powder act as support for the new layers.

Although SLS offers several rapid prototyping advantages, there are some significant disadvantages. SLS was developed in the late 1980s and is still considered a relatively new manufacturing process. While research is continually being performed to improve efficiency, not all SLS builds are considered successful, and many problems still exist with the process. The main difficulty facing SLS researchers is the need for the process to occur within a completely enclosed and sealed chamber. The sinterstation has a front window for users to view the process; however, little else can be done while the sinterstation is running, thus eliminating any human intervention. While data can be easily collected either before the build has started or after it has completed, certain specific questions regarding the build process remain unanswered.

SLS has the ability to produce parts from a wide variety of powdered materials, including metals, ceramics, and polymers. A popular powder material choice is polymers, due to their relatively low melting temperatures, low surface energies, and high melt viscosities [2]. A lower melting temperature requires less energy and, therefore, is conducive to a more economical build. Although several types of polymers can be used in SLS, nylon is a very popular choice. Due to polymer porosity, some finished polymer parts exhibit slightly lower mechanical properties than the cast material from which they are made. Because nylon is a semicrystalline polymer with higher sintering rates and a lower melt viscosity, the porosity effects on the final part are minimal and assure densities very similar to the cast material. These high mechanical properties create durable final parts and prototypes.

A disadvantage to using polymers in SLS applications is shrinkage and subsequent warping. Nylon, specifically, exhibits a high degree of shrinkage due to its semicrystalline structure. As the nylon powder crystallizes, each layer shrinks slightly above the previous layer. Semicrystalline powders generally shrink between 3% and 5% [2], a percentage that can be accounted for while designing the part. However, it is not always guaranteed that the shrinkage or warping will be uniform throughout the part. Because of the possibility of nonuniform shrinking, nylon is sometimes an unreliable material to use when part accuracy is of high importance.

The entire SLS process is, essentially, governed by the transfer of heat from a laser to a chamber filled with powder particles, causing subsequent fusion. Although it is possible to change the laser's energy to manipulate the amount of heat transferred, it is more feasible to keep the energy output constant and, instead, alter other factors influencing overall heat transfer. One of the most significant influences on heat transfer is the powder bed temperature. The powder bed's surface must be kept within a specific temperature range. It must be slightly below the melting temperature to reduce the effects of shrinkage but should not be high enough to melt and fuse the surrounding powder particles. Semicrystalline polymers, such as nylon, have a very small range of part bed operating temperatures. The temperature below the surface of the bed can also influence the final part. Parts formed early in the build have much more time to cool than parts formed toward the end. This inhomogeneous cooling could potentially cause thermal stresses, which, when unbalanced, cause warpage [2]. Another area of concern is the in-build distribution of parts. How close and far apart the parts are built in respect to each other could impact the subsequent cooling process. Inhomogeneous cooling can also result from parts' being built closer to the build chamber edges, which are slightly cooler. Cold spots on the part bed's surface also represent inefficient sintering areas. An important goal of this research is to recognize where they are located on the surface and eliminate them. By gaining more insight into the thermal properties and temperature profile of the powder bed surface, these issues can be further understood and, eventually, eliminated.

Curling is a significant thermal issue in the sintering process. Curling occurs as a result of thermal gradients that develop between powder layers. Curling is exacerbated by cooler layers deposited over previously sintered warmer layers. This causes the edges of the newly deposited layer to curl upward and impair the adhesion to the underlying layer. It is possible to avoid curling by raising the powder temperature, however, if the powder is too hot it will melt the surrounding particles and spread unevenly. The ability to know the thermal behavior at the part bed's surface could eliminate curling by ensuring the surface is kept at an exact, uniform temperature.

Although SLS was recently developed, a significant amount of research has been done regarding the temperature behaviors. Several methods have previously been investigated to provide further insight into the part bed's temperature behavior. Most of the previous research conducted regarding the temperature gradients involves theoretical numerical models, as opposed to direct measurement. Temperature measurements of other methods of freeform fabrication have been investigated. While the other methods are similar in some aspects, they do not take place in fully enclosed chambers and are, therefore, easier to record data externally.

In 2004 Schultz developed a "one-dimensional closed-form analytical solution for heating of a semi-infinite body, with a convective boundary condition, by a moving surface heat flux" [3]. From the theoretical model he created an accurate depiction of the laser's energy behavior and how it affects the surface. He then used this model to approximate temperature values for the part bed. Following his theoretical work, he sintered specimens of polycarbonate (PC) and polyethylene-oxide (PEO) to test his predictions. He finally concluded that "convective heat loss from the surface during laser sintering has a negligible effect on the temperature distribution in the powder-bed".

Although he tested his predictions, the basis of the research was primarily theoretical and did not utilize any type of external measurement of the part bed surface.

L. Dong *et al*. modeled the part bed temperature using a three-dimensional finite element method. The research was performed specifically for Nylon 12 powder and shows a theoretical depiction of the temperature distribution [4]. Their research was based on a previously developed model made specifically for sintering amorphous polymers powders. The model was recreated to analyze semicrystalline polymer powders and accounted for latent heat during the melting process. They also investigated the temperature's effect on powder density. This research was predominantly theoretical and although an accurate model was created, it did not directly measure the temperature of the part bed surface or give a complete depiction of hot or cool spot locations.

Kandis *et al.* also performed research on SLS temperature behaviors. Their work developed another theoretical model but was more concerned with the laser's instantaneous effect on the surrounding powder in the heat-affected zone [5]. Their goal was to predict the exact behavior of the heat-affected zone during the sintering of polymer powders. The researchers made predictions on the heat-affected zone's characteristics and compared them to experimental results. They used their final model to analyze how different temperature parameters affect the overall sintering process. This research dealt mainly with the powder particles surrounding the laser beam's focus. It did not give a complete analysis of the entirety of the part bed surface.

Hopkinson researched the temperature behavior during high-speed sintering [6]. High-speed sintering fuses 2D layers of powder without a laser. A thermal imaging camera was used to monitor the powder temperature and ensure uniform heating. High-speed sintering does not pre-heat and therefore the IR camera was crucial to monitoring the surface temperature. Although high-speed sintering is very different than SLS, the process used to monitor the surface temperature was similar to the goals of this research project. High-speed sintering does not take place inside a fully enclosed chamber in the way that SLS does. Because of this, it was much easier to aim the camera at the powder bed surface and obtain accurate readings.

Beuth investigated temperature behavior in several types of layered thermal modeling— which included laser sintering [7]. He derived a one-dimensional heat transfer model to demonstrate the temperature's behavior. Beuth modeled the residual internal stresses following the sintering and cooling processes as an elastic beam. Although this research directly dealt with modeling the temperature behavior, it was mostly focused on the internal stresses within the final part rather than the powder surrounding it.

Benda conducted significantly important research regarding the temperature control issues of SLS [8]. He developed a method to maintain a steady powder temperature through controlling the laser's output power. A sensor monitored the part bed's temperature at the exact location of the laser beam's focus. The method took thermal conductivity and powder reflectivity into account. It also accounted for the temperatures of the previously sintered layers and how they influence the newer layers. He also developed a second, larger laser beam which was capable of controlling greater areas of surrounding powder. He finally proved that it was successful in reducing the effects of curling. This greater degree of laser control was useful in making more accurate parts but did not show other areas of the part bed aside from the sintering points.

Overall, the research that has previously been conducted regarding thermal measurement of solid freeform fabrication has been mostly theoretical. Although some have managed to obtain accurate temperature readings, they were done under different circumstances and did not show a complete part bed image. While it is helpful to know the temperature behavior at the exact point of the laser beam, it is also very important to understand how the rest of the part bed is affected.

Chapter 2: Research Objectives and Constraints

Nylon's thermal issues during SLS builds are a major concern during the sintering and cooling processes. Although nylon has many strong advantages, its tendency to curl reduces nylon’s viability as a material choice. To correct nylon’s curling and warpage issues, a better understanding needs to be formed regarding the temperature gradients on the part bed's surface. By gaining further insight into the melting and cooling processes, a more accurate depiction of the temperature profiles can be obtained.

The main difficulty in obtaining temperature information is gathering the needed data while the sinterstation is operating. While taking measurements of the powder bed immediately after the laser has finished its final scan and the sinterstation door has been lifted is fairly simple, that information is insufficient. The best way to gain the most complete understanding of the bed's temperature profile is to aim an infrared camera directly at the surface. An infrared camera will provide a complete image of the bed and will demonstrate how each area's respective temperature relates to the rest of the surface.

The primary goal behind the thermal imaging data acquisition is the possibility of expanding the build volume of the part bed. The thermal imaging shows exactly where the cooler spots are located on the part bed. By knowing the locations of these cooler spots, the person operating the build can adjust the heaters to compensate and have a more even control over the part bed’s surface temperature. If the part bed’s surface temperature is entirely uniform, more parts could possibly be fit into a single build, therefore improving overall efficiency. The part bed’s temperature is recorded before and after the build during the heating and cooling of the sinterstation, yielding information that offers further explanation of any temperature nonuniformities. The edges of the build chamber are also important with regard to surface temperature. The edges are kept at a specified temperature that creates a thermal gradient with respect to the rest of the powder bed. The thermal imaging gives a more complete understanding of this gradient and how, exactly, it affects the surrounding powder.

Several constraints govern the overall goals of the research. The first constraint dictates that the part bed's surface temperature be monitored specifically while the build is being performed. This particular constraint is important because it gives an accurate depiction of the thermal behavior during warm-up, the sintering process, and subsequent cool-down. Finding the temperature profile after the build has been completed will only show the gradient following powder cooling. Monitoring the temperature in real-time will show thermal behavior throughout the entire sintering process. Viewing the temperature profile before heating, during powder melting and solidification, and after cooling will more accurately depict the entire process. The sealed chamber and lack of human intervention make this goal difficult. The chamber must remain closed due to the continuous flow of liquid nitrogen during the build. The high-powered laser is also a concern. If the laser is somehow reflected off a surface and redirected, it could, potentially, cause damage. These extreme internal conditions hinder the possibility of operating any type of commercial electronics from within the sinterstation. Not only would the electronic parts circuitry be compromised, the reliability would also suffer. Therefore, the temperature profile must be obtained from outside the sinterstation.

Another main goal of this research is to obtain a complete temperature profile of the entire powder bed surface. Thermocouples placed in varying locations on the surface could give specific temperature readings; however, this information would be insufficient. This research aims to simultaneously view the full part bed surface, including the edges. It is necessary to see how the temperatures of the edges relate to the middle and how they vary with respect to the part locations.

The proposed method uses an infrared camera equipped with a wide-angle lens to externally monitor the powder bed's surface. The camera accurately captures a thermal image of the part bed's surface, thus showing how the edge temperatures relate to those in the center. The infrared camera is also easily adjusted to a specific range, including extremely high temperatures. It is able to run continuously as the build is in process and can capture a series of desired pictures. The part bed surface temperature can be viewed on a computer screen as the sinterstation is in operation, an option that offers a large, clearly colored picture. The camera can also be controlled using FLIR's ResearchIR software. The software can control the camera and command it to capture a series of images at given time intervals. These captured images can be saved for subsequent temperature analysis. The software also gives complete customizable freedom to the camera operator and can control how many images are captured and how much time elapses between photos.

Chapter 3: Thermal Imaging Apparatus Design and Construction

The build was run on a *Sinterstation 2500* (Figure 1), manufactured by DTM Corporation. There are three powder chambers: two feed bins and the main build chamber. The build chamber is located between the feed bins and is where the sintering occurs during part construction. The feed bins supply the powder for the build. The powder is then evenly distributed by a roller. The roller moves back and forth before and during the build to spread new powder layers. Heaters located exactly 9 inches over and directly above the build chamber surface raise the powder temperature as needed. These heaters are responsible for bringing the powder beds to the desired operating temperatures.

A FLIR A325 thermal imager (Figure 2) is the camera chosen for use in this experiment. It has a 320x240 pixel resolution and a 16-bit resolution. The camera meets several important criteria and is an appropriate choice for the thermal imaging of the part bed's surface. The A325 is equipped with an important feature— a high-temperature option. For this experiment, the camera must be capable of capturing high temperatures when necessary because of the sinterstation's internal temperatures. The camera's high-temperature capability easily reads temperatures up to 2,000 degrees C, although the surface measurements in the sinterstation do not exceed 500 degrees C. Another important feature noted when selecting a camera was operating temperature. Although the camera will not be inside the sinterstation, it will be touching the outside window panel, which reaches about 45 degrees C. The FLIR A325 is operable up to 50 degrees C, a temperature that is well above room temperature, and that ensures the camera's ability to withstand the external conditions. The chosen camera model is also relatively lightweight. At slightly over 2.5 pounds and only 10 inches long, the camera's compact size and light weight make it easy to manipulate and mount to any desired locations. The camera requires little support and can attach easily to the sinterstation. It also attaches readily to most tripods, which can provide stability and reduce vibrations caused by the sinterstation.

Figure 2: FLIR A325 infrared camera [9]

One of the strengths of the A325 is its compatibility with the FLIR ResearchIR software. ResearchIR can customize how the camera collects data, command its functions, and control the entire system. This software program makes capturing images much easier and customized. The user can completely control how many images are captured and can designate intervals between images. The program can also analyze temperatures at any given screen pixel, a capability that enables convenient thermal analysis. The FLIR A325 connects to computers through a standard Ethernet cable, making connectivity quick and simple. The program also measures a specified geometric area's temperature. If desired, the user can draw a line, rectangle, or sphere on the output display screen. The ResearchIR can analyze the drawn shape separately by displaying the minimum, maximum, and average temperatures of the designated area. Overall, the ResearchIR program is accurate, is user-friendly, and provides the necessary types of measurement capabilities, and its maximum potential is realized through its compatibility with the FLIR A325 camera.

One issue involved in the thermal measurement design is determining where to place the camera. To place the camera inside the sinterstation is not feasible, so an appropriate external location must be chosen. This location constraint is necessary to meet the goal of monitoring the temperature during the build. It is very important that the sinterstation can run and perform builds without the infrared camera and thermal measurement devices, so the entire setup must be easily removed and reattached as needed. The goal is to make as few changes to the actual sinterstation as possible. Although it would be possible to drill a hole through one side and to aim the camera toward the part bed surface, this change would cause permanent damage to the sinterstation, and the hole would need to be closed up somehow to allow for normal builds. The easiest solution would be to simply aim the camera through the front window. This solution will not work because of the triple-paned glass used as the existing sinterstation's window. The infrared images are completely reflected off the surface, and nothing can be displayed from the camera. It would be feasible to drill a hole through the existing glass window; however, once again, this solution causes permanent damage to the sinterstation.

The final solution involves aiming the camera through the front opening of the sinterstation but through a new window. The existing window is simply bolted in and held in place with an adhesive. By taking out the original window and replacing it with a new window design, the system will be completely customized for the experiment. Removing the window also makes it possible to attach the camera to the new window with clamps, which will hold it in place and keep the camera close to the part bed surface. This design works because removing and replacing the front window result in no permanent damage done to the sinterstation by removing the front window. If needed, the original window can be easily reattached with adhesive. The new window design also gives the freedom to run the sinterstation without taking any thermal measurements, if desired. Although external viewing is limited with the camera attached, the new window does not change the basic functions of the sinterstation in any way. If it is necessary to view the progress of the build or see anything inside as the sinterstation is running, it is still possible (although not ideal) with the infrared camera. Overall, this design solution meets all necessary criteria for the permanent operation of the sinterstation while still allowing all required measurements.

To completely ensure that the camera does not overheat, it was placed inside a protective housing (Figure 3). The housing box is manufactured by Allied Electronics. It is made of steel and measures 8 inches by 14.25 inches by 10 inches. The housing provides adequate space for the camera and its additional rear wiring.

Figure 3: Allied Electronics housing for camera [10]

To provide air circulation around the camera, thereby cooling the camera several degrees during operation, a 12V fan manufactured by Bi-Sonic is attached to the housing (Figure 4). It measures 60mm by 60mm by 25mm and fits easily on the side of the housing (Figure 5).

Figure 4: 12V fan attached to housing

Figure 5: Camera housing with fan located toward front

The hot air escapes through a 2-inch diameter hole cut in the bottom of the housing (Figure 6). The camera is a very costly piece of equipment, and this simple solution ensures it is not damaged by the extreme external temperatures. Several openings are professionally cut in the steel housing to fit connectors and specific cords used to operate the camera. These connectors will also benefit from the cooling provided by the fan.

Figure 6: Bottom of housing with air escape hole

To determine how close to mount the camera and its housing to the powder bed, it was first necessary to perform field-of-view calculations. Ideally, to capture the widest field of view, the camera must be placed as close to the front window as possible. A major goal of the experiment is to capture the thermal image of the entire part bed at one time. Achieving this goal is important to allow for easy comparisons of different areas of the part bed surface. A series of calculations were performed to determine what field-of-view angles are necessary to capture the whole part bed surface with the camera touching the glass. These calculations included both the horizontal and vertical fields of view.

The horizontal field-of-view is 25 degrees. Figure 7 shows a top view of the horizontal field-of-view. To find out how far back the camera needs to be placed to include the entire part bed surface in its field-of-view, a simple geometric calculation was performed (Equation 1). To capture the entire surface, the camera must be placed 27 inches back from the part bed's front edge. This means if the camera is touching the sinterstation's front window, the field-of-view will be insufficient and will not capture enough of the part bed's surface.

$$27\ inches = \frac{6\ inches}{\tan(\frac{25°}{2})} \qquad (1)$$

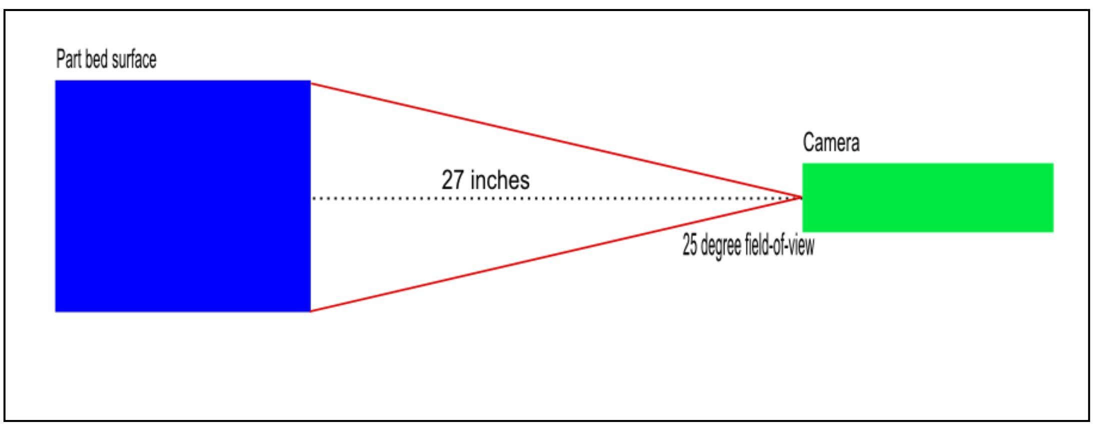

Figure 7: Top view of horizontal field-of-view (drawn to scale)

The vertical field-of-view was more complex than the horizontal. The simplest way to determine the necessary field-of-view angle was to draw an experimental scaled 2-dimensional model (Figure 8). The necessary vertical field-of-view is 60 degrees, a number significantly less than the camera's existing field-of-view—18.8 degrees.

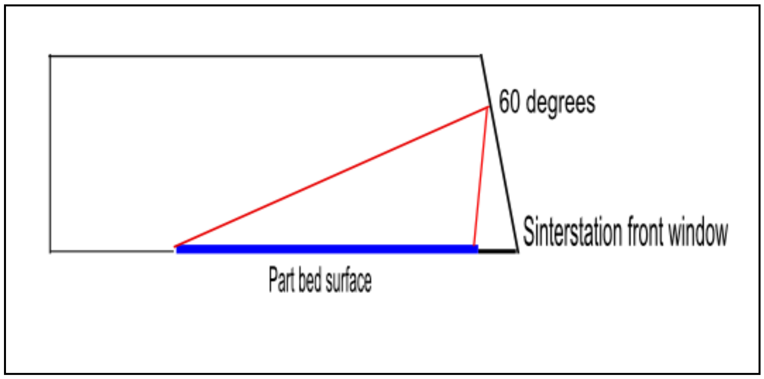

Figure 8: Side view of vertical field-of-view (drawn to scale)

To correct the insufficient field-of-view problem, a wide-angle lens with a horizontal field-of-view of 90 degrees and a vertical field-of-view of 73 degrees was purchased and calibrated to the exact camera. This field of view is sufficient to capture images of the entire part bed surface simultaneously.

The new insulating window was designed in SolidWorks based on precise measurements of the sinterstation's existing window. Detailed SolidWorks three-dimensional models and two-dimensional drawings were generated to accurately reflect the entire design and assembly. The new window design is comprised of two sheets of 1/8-inch thick aluminum, cut and machined to fit inside the window's opening (Figure 9). The two edges of the aluminum sheets are bent toward each other and rest inside the window opening's edges. The camera's steel housing is bolted to the new aluminum window. The first aluminum sheet is glued into the window opening with DAP's black RTD-type 100% silicone high-temperature gasket-sealant to keep it in place. The second sheet of aluminum is held in place with bolts. To ensure even less heat transfer, 8 ½-inch diameter rods made of phenolic (a very good insulator) were cut and placed between the two sheets (Figure 9). These rods separate the aluminum sheets at the desired thickness while ensuring as little heat transfer as possible. Ideally, the outside surface of the new aluminum window should be as cool as possible. A hole was cut in each sheet of aluminum to provide access for the infrared camera lens.

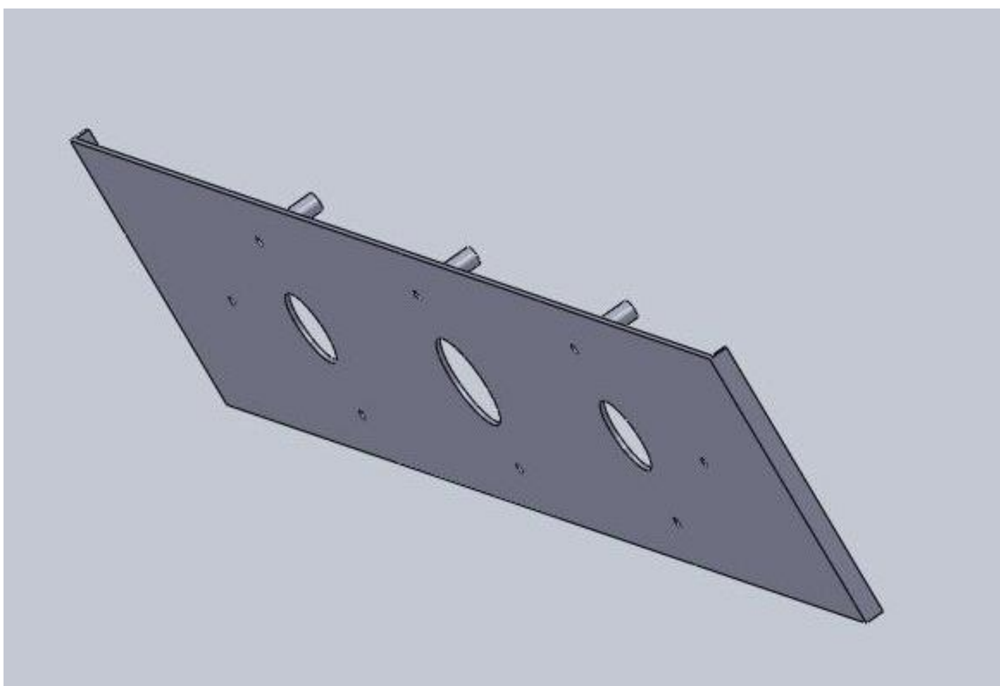

Figure 9: Half of aluminum window with edges bent and phenolic rods

Several design issues and complications with the aluminum window were addressed. Because infrared cameras reflect images off most surfaces, a new material must be used in the window. The best and most common window material choice is Zinc Selenide (ZnSe). Infrared cameras are highly compatible with ZnSe optics when an anti-reflective (AR) coating is applied. To complete the new aluminum window, two round, 2-inch diameter pieces of 0.20 inch thick AR-coated ZnSe were obtained, one for each sheet of aluminum. Because the camera lens will be physically touching the ZnSe window, the pieces of ZnSe must be insulated and kept at a cooler temperature. Aluminum is a highly conductive material and without adequate insulation, the pieces of ZnSe will overheat. A phenolic tube is used to separate the aluminum from the ZnSe. The ZnSe pieces fit directly within the tube's inner diameter, and the tube is then placed inside the holes cut into the aluminum (Figure 10).

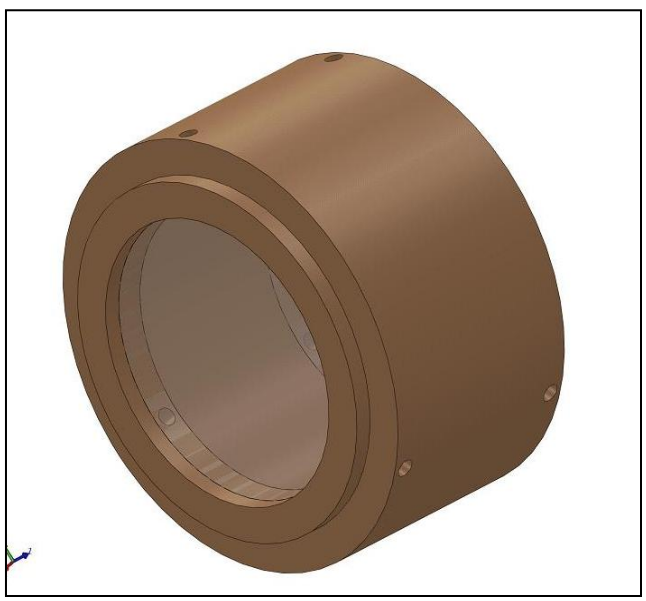

Figure 10: Phenolic tube with ZnSe lenses in place

The new insulating window design does not allow users to see inside the sinterstation without operating the infrared camera. Two small viewing windows are placed on either side of the ZnSe lens for increased visibility. The viewing windows are made of soda-lime tempered glass and safely block the sinterstation's laser from escaping. The windows are made by McMaster-Carr and are 2 inches in diameter. Two of these windows were placed on the front of the aluminum assembly and two were placed on the back (Figure 11).

Figure 11: Soda-lime tempered glass viewing window

Upon completion of the finalized window and housing designs, construction began. The ZnSe lenses and phenolic insulating tube were modeled in SolidWorks (see Appendix) as an assembly, which includes two sets of three set screws to hold the lenses securely in place. The set screws are placed 120 degrees apart from each other to ensure added lens stability. The ZnSe lens assembly fits into another assembly which includes the two panels of aluminum and phenolic insulating rods (Figure 12).

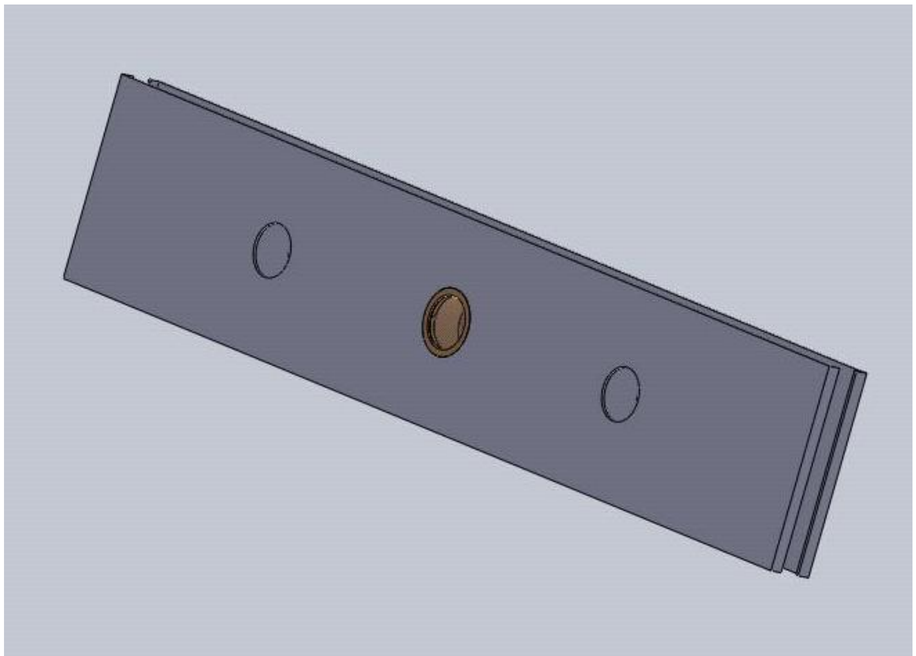

Figure 12: Aluminum window with phenolic tube assembly in place

The camera housing design and window attachment parts were manufactured next. Several holes were machined into the housing for the final camera assembly. The holes were based on the connector dimensions given by their respective manufacturers (Figure 13). Because the camera connects to a computer via Ethernet cable, an appropriate connector was obtained and fitted into a specified hole in the housing. The power supply was subsequently connected using the same method (Figure 14).

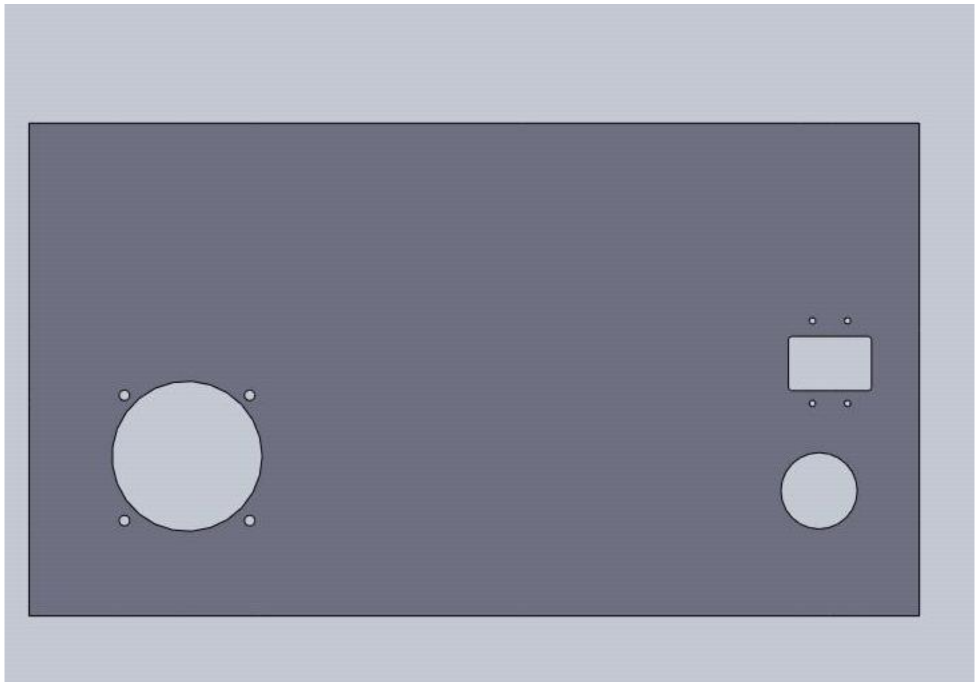

Figure 13: Side of housing with machined holes

Figure 14: Power supply and Ethernet connectors

By wiring the camera inside the housing and using connectors, the user is able to plug the Ethernet cable and power supply into the side of the housing without disturbing the camera assembly. Another customized hole was cut into the housing to fit the specified fan. The fan is also wired internally to continually run while the power supply is connected. The fan is placed on the side of the camera housing near the front lens. It is placed in this exact location because the lens will likely be the hottest part of the camera, and keeping it at a cool and safe operating temperature range is very important (Figure 15).

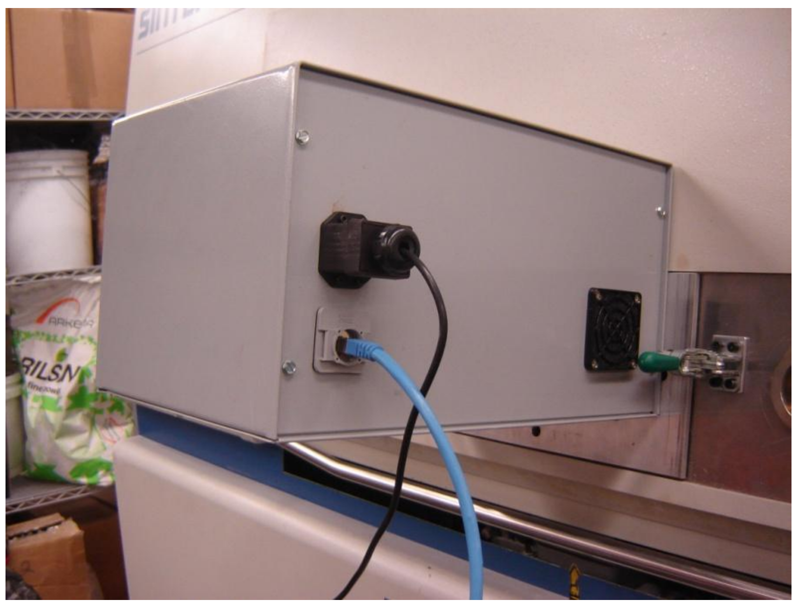

Figure 15: Assembled housing with connectors attached to sinterstation

The final modification to the steel housing box is the air escape hole cut into the bottom. Following this modification, the camera is wired into the housing and held securely in place through the camera's existing bottom tripod holes, creating a semipermanent assembly. The camera is not easily taken out of the housing and will not be removed unless absolutely necessary. The housing also provides extra protection for the camera in the sinterstation lab. Powder particles are airborne in sinterstation labs and can settle in a manner similar to dust. Because the camera is completely enclosed in the housing, it does not face the risk of powder particles' settling on its surface.

The last step in construction is creating a way to attach the camera housing to the new insulating aluminum window. The housing cannot be permanently attached to the window because the front panel of the sinterstation must be opened and closed frequently to access the build chamber and powder. The final design includes a 6 inch by 12 inch by ½-inch thick panel of rectangular aluminum bolted to the front of the camera housing (Figure 16). The rectangular panel is several inches wider than the front face of the camera housing and can be attached to the insulating sinterstation window using De-Sta-Co horizontal handle hold-down toggle clamps. The clamps are fixed to the aluminum window and, when the aluminum housing is placed against it, the two clamps can firmly secure it using the wider rectangular panel (Figure 17).

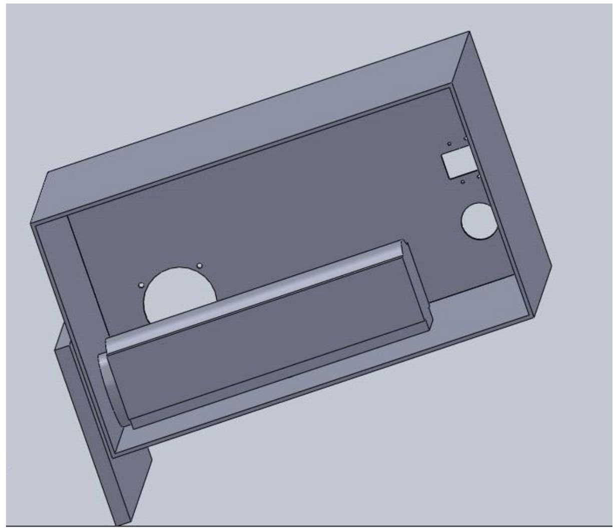

Figure 16: Housing with aluminum panel and camera

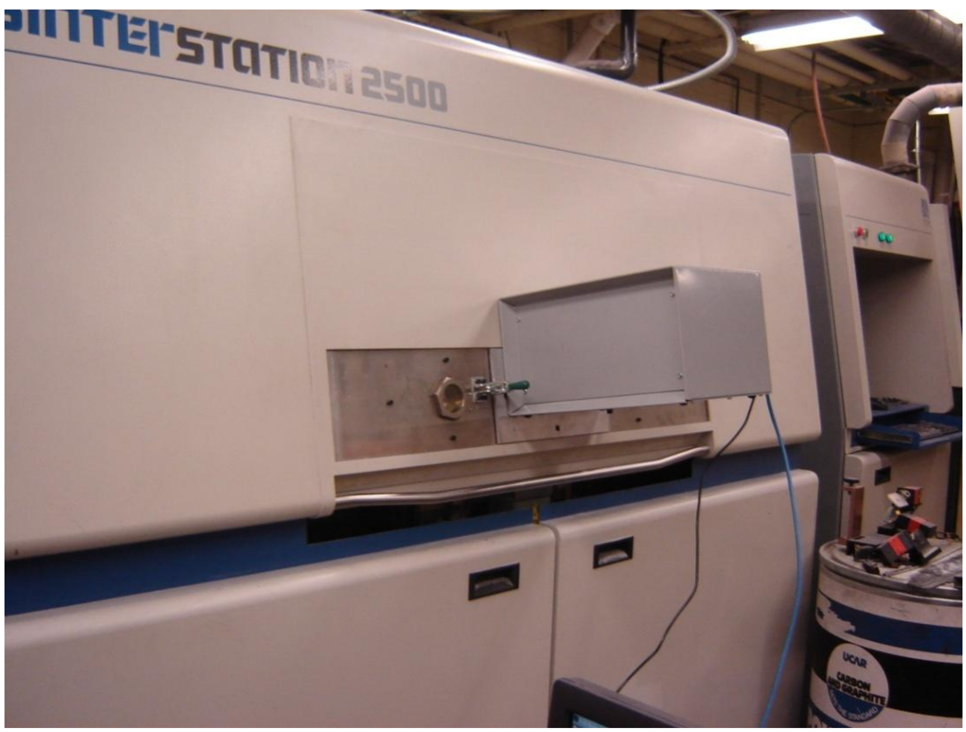

Figure 17: Housing attached with clamps to new insulating window

Before the existing window was removed, it was important to test the camera with the new insulating window. After successfully aiming the camera through the new window and observing accurate temperature readings, it was clear that the design was complete and ready for installation. The first step was removing the existing window. The two panels holding the existing window in place were unscrewed and removed. Next, a knife was run along the edges of the window to break the adhesive seal. The window easily came out and was kept for future use whenever needed. The new window was put in place, and the two panels were screwed in again. The window was finally sealed into position using the RTD-type 100% silicone high-temperature gasket-sealant. The adhesive was allowed to set over a weekend to ensure adequate time. Subsequent inspection showed the window was completely secured into place.

After the new window was successfully installed and the housing assembly was clamped in place, it was necessary to test the field of view and the functionality of the entire design. The camera was turned on and connected to the ResearchIR software to analyze the output. The display showed the majority of the part bed surface with only two corners' being slightly cut from the field of view. This clipped view could be attributed to the thickness of the phenolic tube and window assembly, which was not taken into account during previous calculations. Although the part bed surface is not shown in its entirety, the thermograph is still, overall, a relatively complete depiction of the chamber and manages to capture all areas of interest (Figure 18).

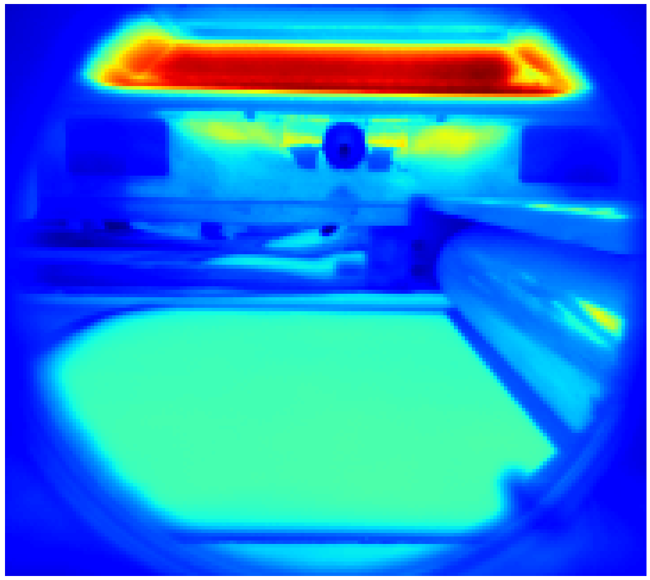

Figure 18: Computer screen view of camera's thermal image

For the main experiment and temperature analysis, a "sheet of paper" was designed to be built inside the chamber. It is only 1 layer of powder and is very thin, but it still exhibits a uniform thickness. It is 25.7 cm by 17.2 cm. This simple part design is perfect for an initial analysis to test the experimental design and will clearly show all areas of concern. The "sheet of paper" also requires a very short sintering time, so this simple build is more economical than complex parts. The "sheet of paper" is centered in the part bed and fills the majority of the surface area.

The experiment is composed of four main segments of time. The first segment analyzed is the part bed heating. During this time, the sinterstation is increasing its power output to raise the part bed temperature to prepare for the sintering process. The warm-up process happens slowly, allowing the temperature to increase over several hours. The next time segment is powder layer deposition. The roller begins continuously spreading powder over the part bed. As the roller glides over the surface, the new powder heats up, and the process significantly contributes to the temperature distribution of the surface area. The third and most important segment of time analyzed was the actual sintering. Although the part is extremely thin and consists of only 1 layer of sintering, this simple sintering process is crucial to the overall temperature analysis. The final time stage analyzed is the cooling process. Following sintering, the machine must cool down for several hours before the build can be removed from the chamber. This stage is important because the cooling process plays a vital role in how the particles fuse together.

The *Sinterstation 2500* (Figure 1) requires a particularly long heating time and, therefore, was allowed to heat overnight. Upon reaching the target temperature of 353K, ½-inch of powder was deposited, continuing the warm-up process. When the surface measured 451K, the roller began moving and depositing 0.004-inch layers across the part bed. In this experiment, the first of these layers required 18 minutes to heat; following this deposition, the remaining layers spanned 68 minutes. The sintering process immediately followed and lasted a total of 9 minutes to complete the area of the "sheet of paper." Upon completion, another ½-inch layer of powder was deposited on top of the part, and cooling followed.

The IR camera did not begin capturing data until the morning of the build and, therefore, did not monitor the bed's surface beginning at ambient temperature. The camera was plugged into the power source and began collecting data as the part bed temperature was being raised from 353K to 451K. During this time, the camera was set to capture a single image once every minute. The camera continued on this cycle and captured an image per minute while the roller was moving and depositing the powder layers. The entire sintering process was recorded and saved as a series of image files. The camera was then set to capture an image every 5 minutes to depict the temperature behavior during the cooling process. After the sinterstation cooled, the part was removed from the powder bed. The images were grouped together and sorted to find areas of interest and nonuniformities throughout the various stages of the build.

Chapter 4: Results and Discussion

The infrared camera was able to capture the majority of the part bed's surface. Along with the rectangular surface, the camera also reads and displays several other parts within the sinterstation. In the resulting thermographs, the temperature scale displays the color gradient demonstrated in the image. Figure 19, which was captured toward the end of the warm-up stage, shows temperatures above 480K as 480K and, similarly, shows all temperatures below 360K as 360K. The scale was easily adjusted to show gradients and larger temperature differences as needed.

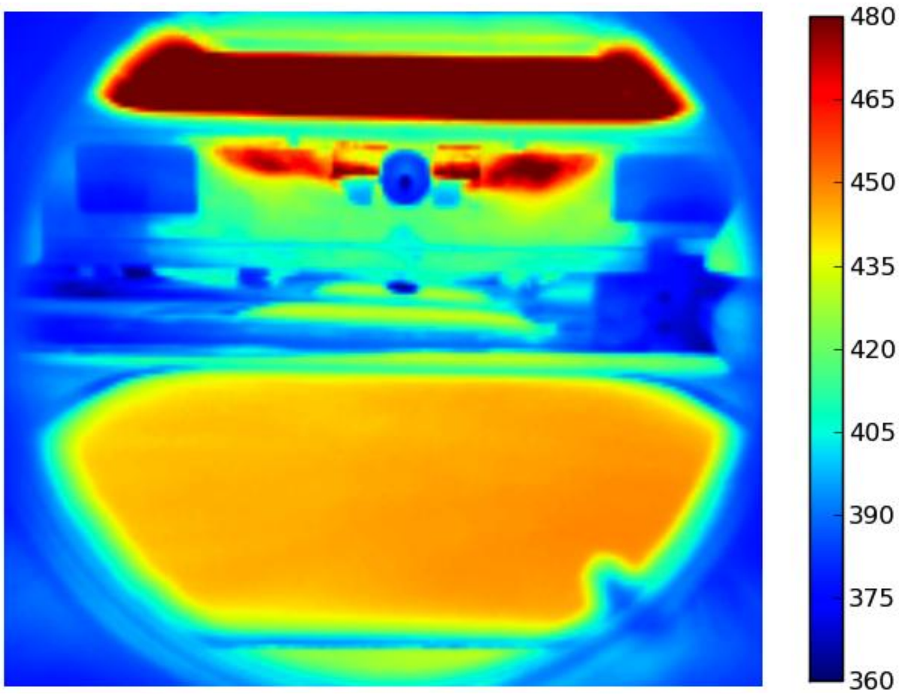

Figure 19: Thermograph taken toward the end of warm-up stage

The extremely high temperature reading in the thermograph depicts the radiant heater located directly above the surface of the part bed. The image appears to be inside a circle, which is actually the inside of the insulating phenolic tubing. The sinterstation's internal IR sensor is located in the image below the radiant heater and is shown as a small circular cool spot. The two hot areas shown on either side of the IR sensor are the heater's reflection. Another reflection inside the sinterstation shown in the thermograph is from a stainless steel baffle located on the back edge of the chamber. The baffle is highly reflective and clearly shows the powder bed's surface image in the center of the thermograph. The powder bed takes up the majority of the lower half of the image and is shown clearly as a rectangle (viewed at an angle) with clipped edges. A small intrusion at the bottom right corner of the part bed is one of the three set screws used to hold the ZnSe lens in place within the phenolic tubing.

Adjusting the scale on the thermograph shows a clearer depiction of how the temperature varies on just the part bed. Figure 20 shows an altered image of the part bed with a different scale. The image clearly shows that a thermal gradient exists, with the greatest variation occurring between the top left corner of the image and the bottom right. The temperature on just the surface of the bed varies about 13K, which is a significant difference. Upon closer inspection, the temperature variation is also slightly evident in the previously shown Figure 19.

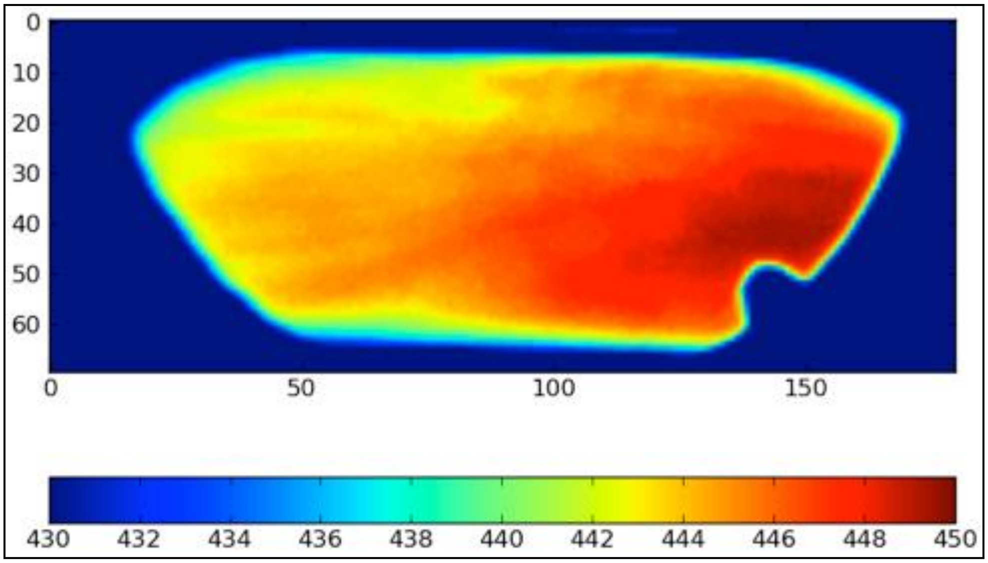

Figure 20: Close-up of the part bed surface with altered temperature scale

To further investigate the cause of the gradient, the camera was removed from its housing and aimed toward the heater following the sintering process. The thermograph shown in Figure 21 was captured and the scale was adjusted to better depict the exact gradient. The edge of the heater located at the top of the image heats the front of the part bed, while the bottom edge shown in the thermograph corresponds to the back of the bed. It is evident that the radiant heater is not at a uniform temperature, with a difference of about 30K from the left side to right side, where the hottest spot is located.

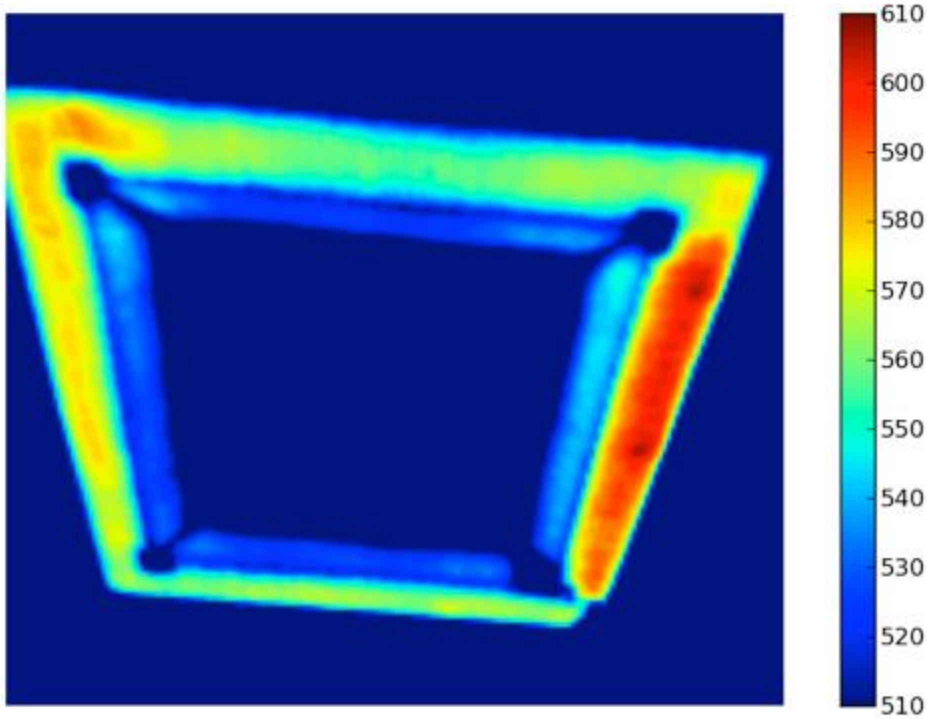

Figure 21: Heater thermograph

During the heating process, the surface temperature starts to exhibit a small thermal gradient, as previously discussed. Figure 22 shows the part bed surface during the build immediately after the laser finished scanning the surface but before the roller spread the next layer of powder. It was captured seconds after the laser finished scanning and the "sheet of paper" was completed. This thermograph was taken just before the next layer of powder was rolled above the part. It is obvious in this image that the right side of the part bed is heated to a higher temperature than the left.

The outlined "sheet of paper" in Figure 22 appears cooler than the surrounding powder. The nylon powder has a high emissivity and is relatively diffuse before sintering. The powder is smoother after sintering and becomes specularly reflective at the viewed angle. This causes the camera to capture the reflection of the cooler wall behind the powder bed.

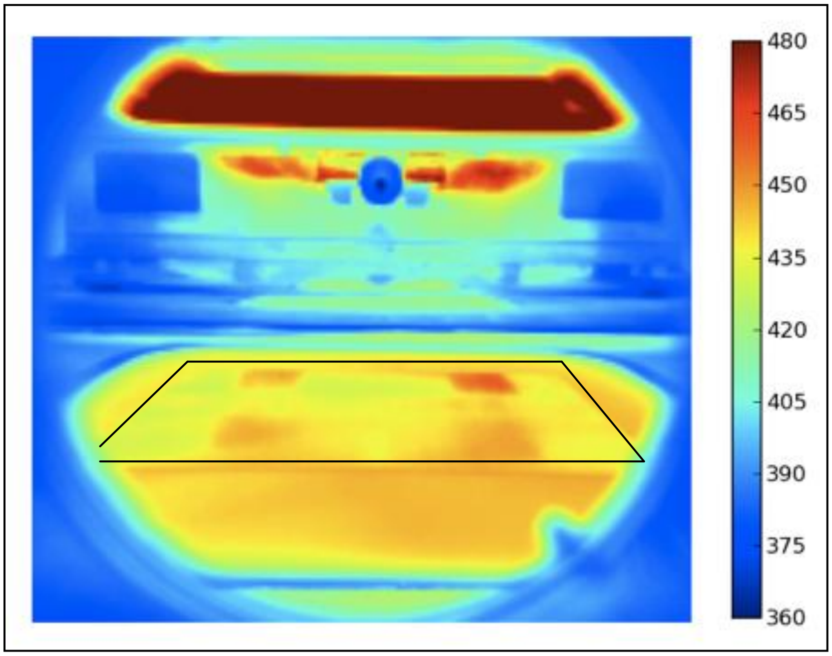

Figure 22: Thermograph immediately following sintering completion

Following the sintering process, two more images were analyzed. The first of these two images shows the part in the chamber just before the roller moves past it, and the second shows the surface immediately after the roller has deposited powder. Figure 23 shows the part bed surface with the "sheet of paper" clearly sintered. The roller is located to the left and has already begun moving. The thermograph demonstrates the relatively small powder bed temperature difference in the time between the laser scanning and the roller depositing powder. It is clear from Figure 23 that the surface exhibits the hot spot due to the radiant heater, shown on the right side of the thermograph.

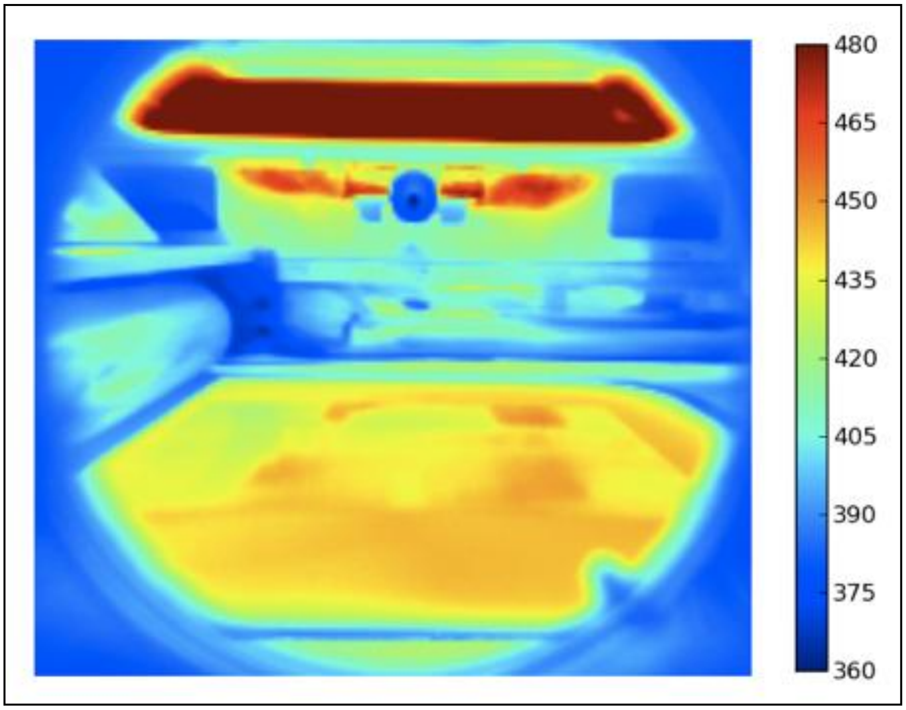

Figure 23: Powder deposition by the roller after sintering the “sheet of paper”

The next layer of powder will be affected by both the underlying hot layer of powder and the radiant heater from above. Figure 24 shows the layer of powder deposited over the “sheet of paper” after the roller has reached the right side, which occurs just after Figure 23. Figure 24 also demonstrates the high insulating properties exhibited by the surrounding nylon powder. After the roller has passed over the surface, the powder does not immediately take on the temperature of the part bed. This clearly shows that regardless of the part's location within the build, the temperature of the powder prior to sintering is unaffected.

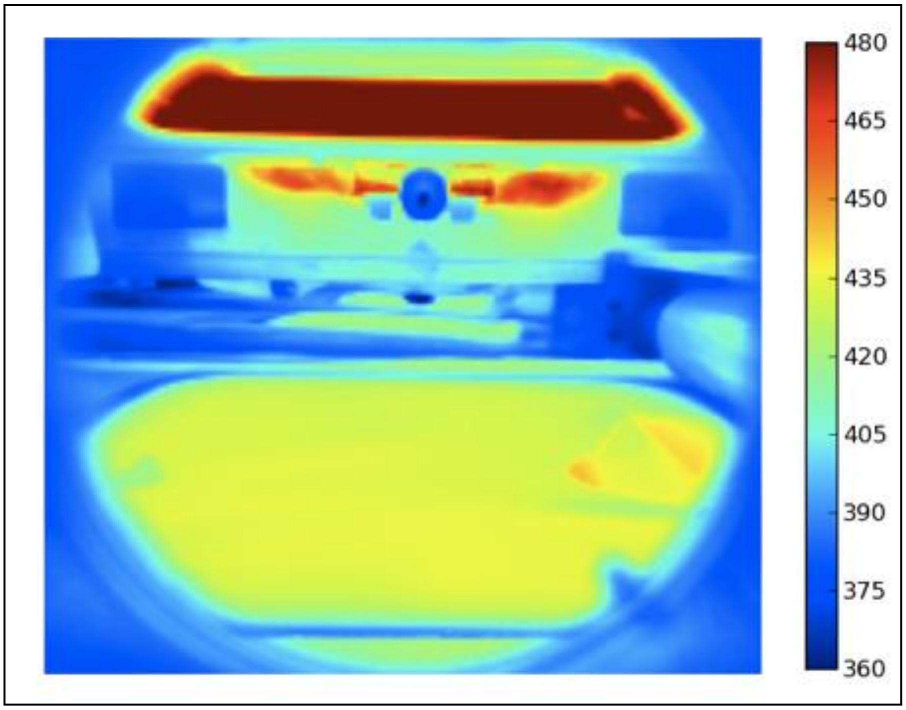

Figure 24: Thermograph after the powder layer is deposited immediately prior to laser scanning

The hot spot on the right still exists, and the new layer of powder is clearly affected by the higher temperatures beneath it. The temperature of the part below the powder layer heats the powder almost instantly and causes the thermal gradient in a matter of seconds. Through the series of thermographs, it is easy to trace how the hot spot from the heater affects the warm-up, sintering, and cooling stages.

The part built for the analysis was designed for simplicity to show hot and cool spots on the part bed. Realistically, most builds will contain parts with much more complex geometries than a “sheet of paper.” The simple part effectively demonstrates where the thermal gradients exist on the surface and can aid in future builds of varying parts. The nonuniformities and thermal gradients on the part bed surface can cause uneven bonding of the powder particles and can subsequently change the part’s mechanical properties. During the breakout process of the part, it was much more difficult to remove the caked powder from the right half of the paper (where the hot spot was located) than from the left half. The breakout difficulties prove that the powders were unevenly sintered and demonstrate the significant difference the temperature gradient has on the build.

Chapter 5: Conclusions

SLS is a relatively new form of additive manufacturing. Because it is such an isolated procedure, monitoring internal temperatures during the process is very difficult for an outside operator. The main goal of this research project was to design, develop, and implement a thermal measurement method that will capture live temperature measurements at various stages throughout the process. The most difficult part of this goal was finding a way to measure the temperature during sintering while the laser is operating.

The final experimental design utilized an infrared camera that was aimed from the outside, front panel of the sinterstation through a specially designed hole and down toward the part bed surface. The existing sinterstation window was removed and replaced with a newly designed window that would fulfill all of the necessary safety requirements. To ensure the new window would not overheat, it incorporated various insulating materials throughout the design. Two ZnSe lenses were placed in the new insulating window, allowing the infrared rays to pass through and aim into the sinterstation.

An external housing was designed to protect the camera and keep it operating at ambient temperatures. A fan was placed on the outside of the housing, close to the camera lens, to provide adequate cooling. The camera was wired through the housing and could be connected to an Ethernet cable and power supply from the rear.

Once the camera and new sinterstation window were in place, the setup was tested in place before parts were built. The design was a success and was able to clearly capture the majority of the part bed surface, as well as many surrounding parts within the chamber. Although the insulating phenolic tube clipped two edges of the powder bed surface, hot spots were still easily detected.

A single build was run on the sinterstation for temperature analysis. The part built was a simple "sheet of paper" that consisted of a single layer of powder. The build consisted of several stages, including a warm-up, powder deposition, sintering, and cool down. The camera was able to capture images and record data successfully at each of these stages and demonstrated thermal gradients and overall temperature distributions.

After analyzing the various stages throughout the build and the images acquired from the camera, it is clear that the radiant heater is not uniformly heating the powder bed. The images showed an obvious hot spot on the far right side of the part. In order to verify the nonuniform heating, the camera was aimed toward the heater itself, and images confirmed that it was much hotter on the right side than on the left. The hot spot on the right side of the part bed due to the nonuniform heater affected the entire build, as can be clearly seen in the thermographs of each stage of sintering. The hot spot continued through the cooling stage and had evident ramifications during the final part breakout.

The uneven heating of the part bed surface caused the layer to be sintered with differing thermal and mechanical properties. The resulting part is nonuniform, and although this build was a simple rectangular layer, these uneven temperatures could have a worse impact on future builds of more complex geometries.

Now that the affect of the heater temperature on the part bed's surface is clearer, appropriate changes can be made when raising the sinterstation's temperature. Knowing the precise thermal gradient and the exact hot spot locations makes the operator more aware of potential unevenly sintered parts. Future research could potentially include a more detailed analysis of part reliability from sintering exclusively in the hot spot area.

Altering the heater temperature to make a more uniformly heated surface area could also be investigated and hopefully would produce more evenly sintered parts.

This research was funded by the Department of Defense under grant #GRT00015778.

Appendix

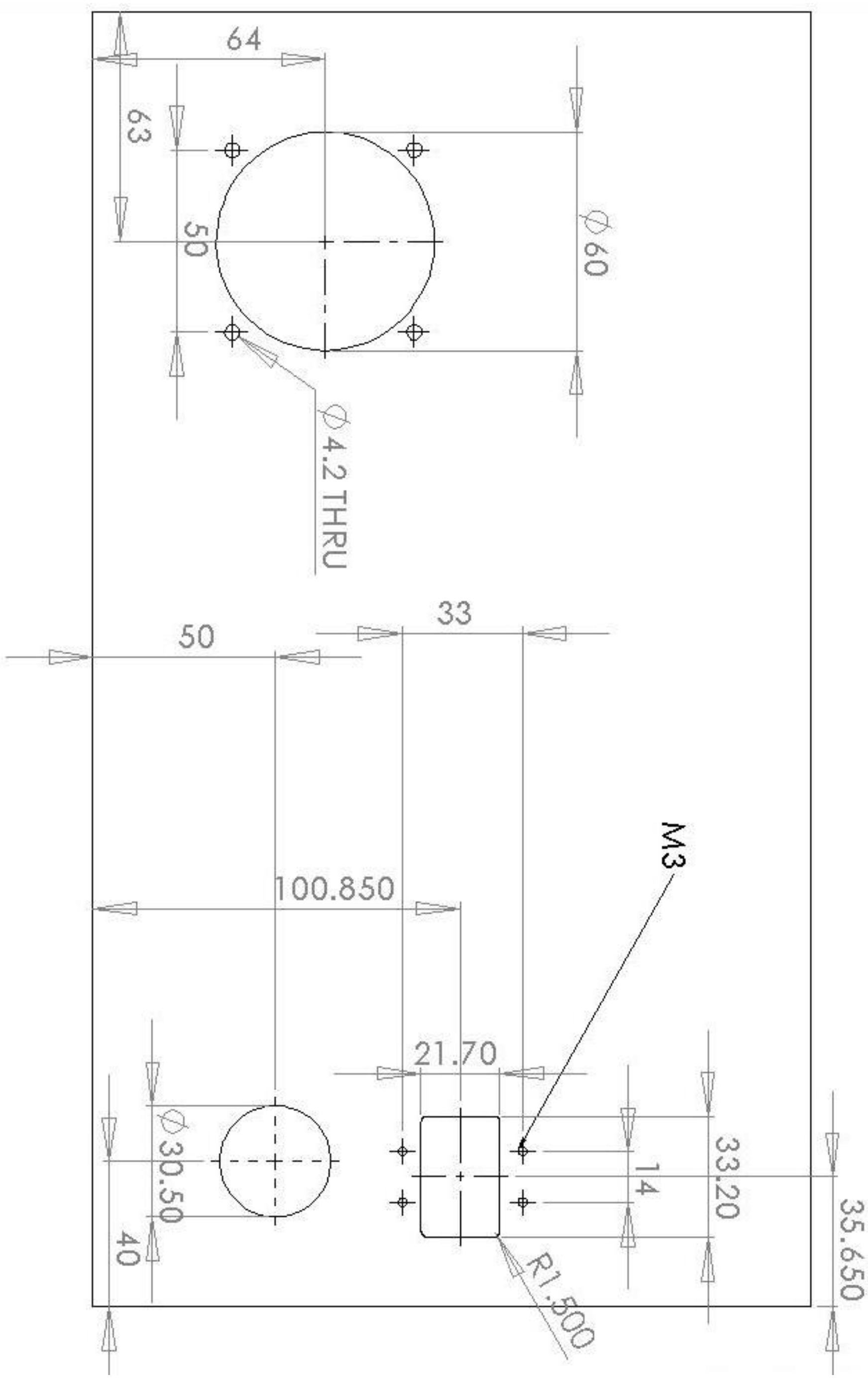

Figure A1: Drawing of connector holes

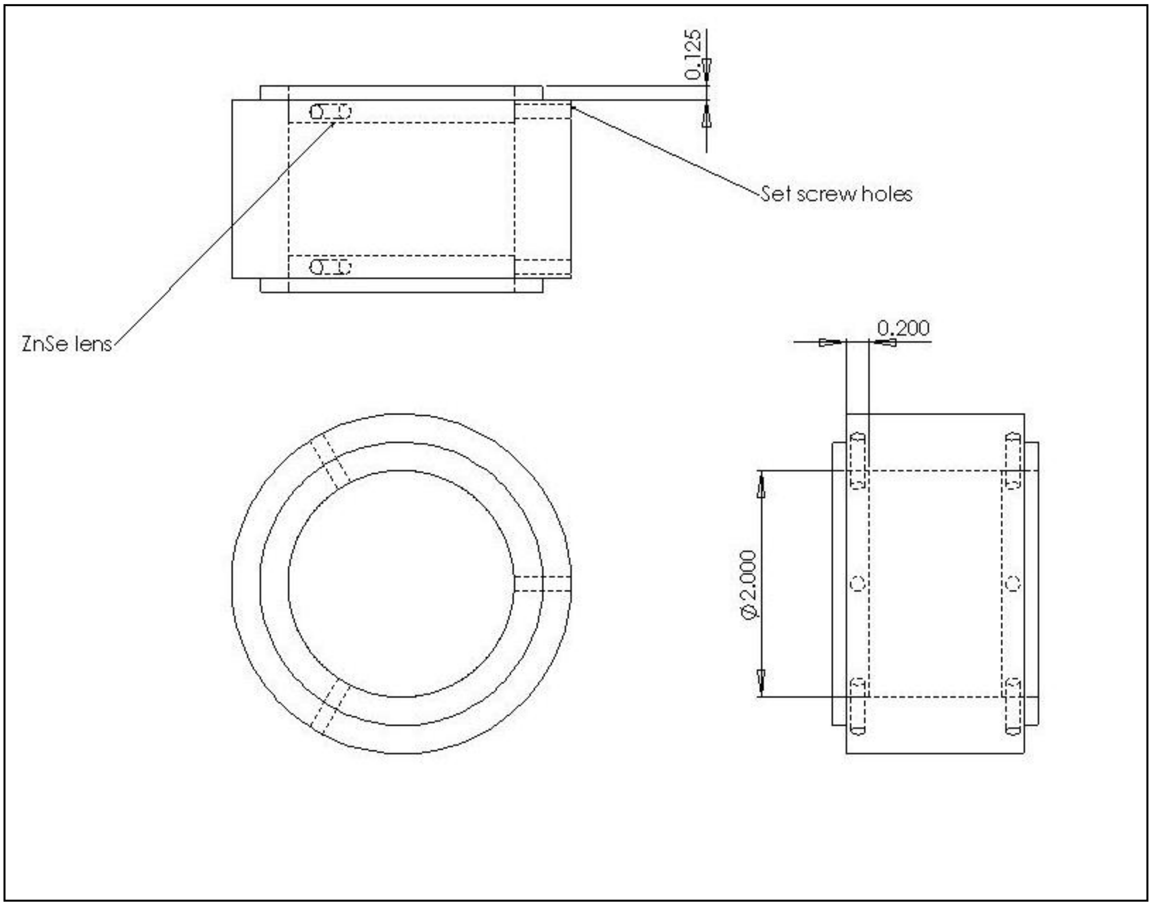

Figure A2: Drawing of phenolic tube and ZnSe lens assembly

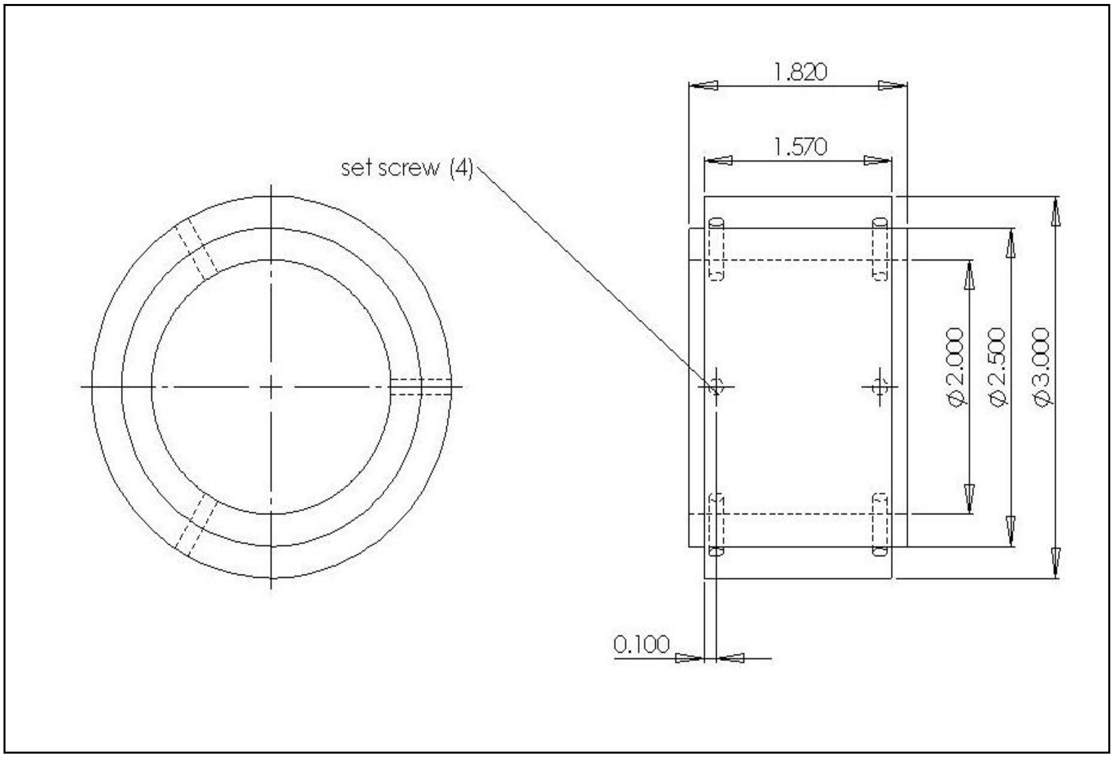

Figure A3: Drawing of phenolic tube

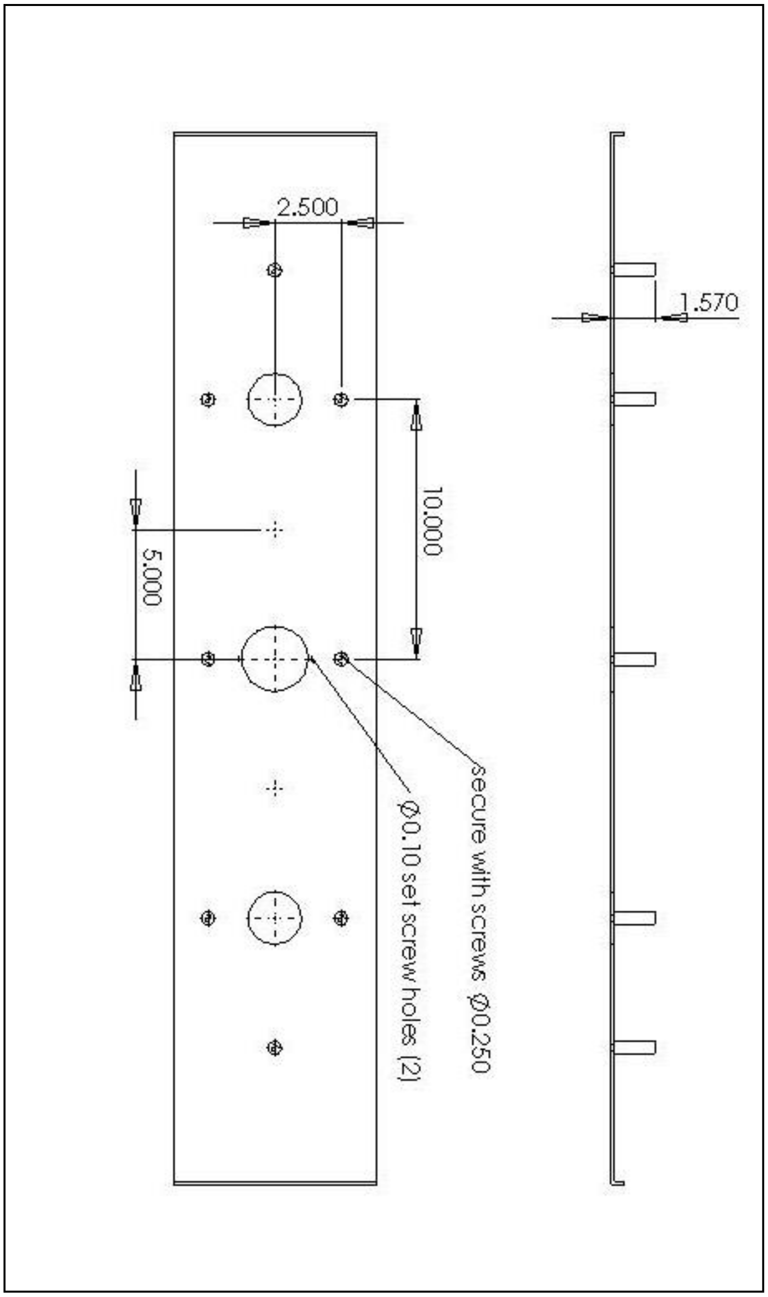

Figure A4: Drawing of aluminum sheet and phenolic rods

References

[1] Http://louisville.edu/speed/rpc/equipment-and-facilities/additive-manufacture-rapid-prototyping.html

[2] Beaman, Joseph J. *Solid Freeform Fabrication: A New Direction in Manufacturing: with Research and Applications in Thermal Laser Processing*. Boston: Kluwer Academic, 1997.

[3] Schultz, J., 2003. \Modeling heat transfer and densification during laser sintering of viscoelastic polymers". PhD thesis, Virginia Tech.

[4] Dong, L., Makradi, A., Ahzi, S., Remond, Y., and Sun, X., 2008. "Simulation of the densification of semicrystalline polymer powders during the selective laser sintering process: Application to nylon12". Polymer Science Series A, 50(6), June, pp. 704-709.

[5] Kandis, M., and Buckley, C., 1999. "An engineering model for laser-induced sintering of polymer powders." Journal of Manufacturing Science & Engineering, 121(3), p. 360.

[6] Hopkinson, N. and P. Erasenthiran, 2004, "High Speed Sintering - Early Research into a New Rapid Manufacturing Process," *Solid Freeform Fabrication Symposium*, Austin, TX. pp. 312-320.

[7] Amon, C., Beuth, J., Kirchner, H., Merz, R., Prinz, F., Schmaltz, K., Weiss, L., "Material Issues in Layered Forming", Proceedings of the Solid Freeform Fabrication Symposium, The University of Texas at Austin, Texas, August 9-11, 1993, 1-10.

[8] J. Benda, "Temperature-Controlled Selective Laser Sintering," to be published in the *Solid Freefonn Fabrication Proceedings,* The University of Texas at Austin, (1994).

[9] Http://www.flir325a.com

[10] Http://alliedelectronics.com

Vita

Janna Hayes LaRocco was born in San Diego, California and moved to Plano, Texas when she was nine years old. She attended Plano Senior High School and following graduation in 2004 she enrolled in the Cockrell School of Engineering at The University of Texas at Austin. In May of 2008 she received the degree of Bachelor of Science in Mechanical Engineering. In the fall of 2008 she entered the Graduate School at The University of Texas at Austin to pursue a master's degree in Mechanical Engineering.

Permanent address: 3404 Mount Vernon Way
Plano, Texas 75025

This thesis was typed by the author.